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Possible Contribution of Mature γ-ray Pulsars to Cosmic-ray Positrons *

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Abstract We restudy the possible contribution of mature gamma-ray pulsars to cosmic ray positrons based on the new version of outer gap model. In this model, the inclination angle and average properties of the outer gap are taken into account, and more mature pulsars can have the outer gap and emit high energy photons. Half of the primary particles in the outer gaps will flow back toward the star surface and emit synchrotron photons, which can produce electron/positron pairs by the cascade of pair production. Some of these pairs will escape from the light cylinder and be accelerated to relativistic energies in the pulsar wind driven by low-frequency electromagnetic waves. Using a Monte Carlo method, we obtain a sample of mature gamma-ray pulsars and then calculate the production of the positrons from these pulsars. The observed excess of cosmic positrons can be well explained by this model.

Key words: stars: pulsars: general — acceleration of particles — ISM: cosmic rays

1 INTRODUCTION

Electrons and positrons are rare particles in cosmic rays. The observation of positrons and electrons can provide an important diagnostic for models of cosmic-ray acceleration and propagation, and also for studies of the modulation of cosmic-ray fluxes by the solar wind. It is generally believed that the electrons are mainly of primary origin, while the positrons are of secondary origin, from collision of cosmic ray particles with interstellar matter. However, compared with the theoretical predictions based on the conventional cosmic-ray propagation models (leaky box model and diffusion model), the observed positron fraction has a significant excess at energies above 10 GeV (e.g., Müller & Tang 1987; Golden et al. 1987, 1994). The observation showed that the positron fraction increases with energy above 10 GeV. So it is reasonable to assume that this excess is due to the contribution from some new source(s).

There are many sources which may contribute to the observed positron excess. It has been proposed that annihilation of dark matter particles in the Galactic halo can account for this excess (e.g., Baltz et al. 2002; Hooper & Silk 2005; Yuan & Bi 2006), and it has also been proposed that gamma-ray pulsars will contribute to the cosmic-ray positrons and can explain the excess at a few GeV energies (Harding & Ramaty 1987; Chi et al. 1996; Zhang & Cheng 2001; Grimani 2004). Based on the polar cap model, Harding & Ramaty (1987) estimated the positron flux and spectrum by assuming that they are produced through electromagnetic cascades. Using the predicted positron production rate, Grimani (2004) found that the contribution from gamma-ray pulsars with a reasonable birthrate is consistent with the observed data. Chi et al. (1996) studied the positron production based on the outer gap model (Cheng et al. 1986). In this model, the synchrotron photons emitted by the returning particles will produce electron/positron pairs in

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the strong magnetic field near the star surface. Zhang & Cheng (2001) have also studied the high energy positron production from mature gamma-ray pulsars based on their outer gap model (Zhang & Cheng 1997). At present, we can not rule out any of these models because of the uncertainties in the models as well as in the observed positron data (Coutu et al. 1999). The recent observed data given by Beatty et al. (2004) are consistent with both theoretical predictions. Here we focus on the contribution of cosmic-ray positrons from gamma-ray pulsars.

More than 1600 radio pulsars have been observed, and none of them with ages greater than 10^6 yr has been observed in gamma-rays: all the nine observed gamma-ray pulsars have ages less than 10^6 yr. In the revised outer gap model (Zhang et al. 2004), taking the inclination angle and geometrical effects into consideration, more mature pulsars can have outer gaps, so possibly they emit gamma-ray photons. It is reasonable to assume that some of these mature gamma-ray pulsars are the counterparts of the unidentified EGRET gamma-ray sources (Cheng et al. 2004). The gamma-ray pulsars with outer gaps can produce positrons. It is believed that pulsars are born in the explosion of supernovae, and are surrounded by the supernova remnants for a certain period. During this period, the produced positron/electron pairs can not escape freely from the surrounding matter. However, more mature pulsars with ages greater than 10^5 yr are not likely to be surrounded by the nebulae, and the produced positron can escape from the light cylinder, and contribute to the cosmic-ray positrons.

In this paper, we restudy the possible production of positrons from mature pulsars based on the new version of the outer gap model. We first produce a Monte Carlo sample of mature pulsars, then determine which ones are gamma-ray pulsars based on the revised outer gap model. We then study the properties of these mature gamma-ray pulsars, such as their spatial distribution. Then we estimate the contribution of positrons by these pulsars. Finally, we give a discussion and conclusions.

2 POSITRON PRODUCTION FROM A PULSAR WITH OUTER GAPS

The outer gaps of a pulsar are powerful accelerators. The huge electric field along the magnetic filed ($E_{\parallel}$) can accelerate electrons and positrons to relativistic energies. In the outer gap, half of the primary electron positron pairs will move toward the star and lose most of their energy via curvature radiation. The residual energy of each charged particle is about $10.3P^{1/3}$ erg, which can produce hard X-ray emissions from the hot polar cap. Most of these X-rays will be reflected back to the stellar surface via cyclotron resonance and re-emitted as soft X-ray photon from the whole surface. In the outer gap, these soft X-rays interact with curvature photons to produce $e^{\pm}$ pairs through photon-photon pair-production process, which sustains a steady outer gap (Zhang & Cheng 1997). The fractional size of the outer gap is an important parameter which determines the properties of the pulsar's high energy radiation. In the revised outer gap model (Zhang et al. 2004), the fractional size f is a function of the magnetic field (B), period (P) and inclination angle (α). These can be estimated by

$$f(r) = \eta(r, \alpha, P, B) f_0(P, B) , \tag{1}$$

where $f_0(P, B) \approx 5.5P^{26/21}B_{12}^{-4/7}$ is the fractional size of the outer gap ignoring the effect of inclination angle (Zhang & Cheng 1997). The function $\eta(r, \alpha, P, B)$ contains the effect of inclination angle, which can be found from equation (37) of Zhang et al. (2004). For a given pulsar, $f(r)$ has a minimum value at the inner boundary, which is determined by ($r_{\rm in}, \theta_{\rm in}$),

$$\tan\theta_{\rm in} = \frac{1}{2}(3\tan\alpha + \sqrt{9\tan^2\alpha + 8}) , \tag{2}$$

$$\frac{r_{\rm in}}{R_{\rm L}} = \frac{\sin^2(\theta_{\rm in} - \alpha)}{\sin\theta_c \sin^2(\theta_c - \alpha)} , \tag{3}$$

where $R_{\rm L}$ is the radius of the pulsar light cylinder, $f(r)$ increases with radius r until it reaches the maximum at r_c if $f(r_c) < 1$ or some distance r_b where $f(r_b) = 1$, r_c is the radius of the last open filed line tangent to the light cylinder. So if $f(r_{\rm in}) < 1$, the pulsar is a γ-ray pulsar with outer gap. In Zhang et al. (2004), the radiation at an average radius $\bar{r}$ is used to represent the typical high energy radiation of a pulsar. We estimate $\bar{r}$ by

$$\bar{r} = \frac{\int_{r_{\rm in}}^{r_{\rm max}} f(r, \alpha) r dr}{\int_{r_{\rm in}}^{r_{\rm max}} f(r, \alpha) dr} , \tag{4}$$

where $r_{\rm max}$=min (r_c, r_b).

The inflowing relativistic $e^{\pm}$ pairs will lose energy through curvature radiation during their motion from the inner boundary of the outer gap toward the stellar surface. When these particles come near the stellar surface, the energy can roughly be estimated as (Zhang & Cheng 2001)

$$E_{\rm e}(r) \simeq 12.3 P^{1/3} [\ln(r_{\rm in}/r)]^{-1/3} \ {\rm erg}. \tag{5}$$

These primaries will emit curvature photons with a typical energy of

$$E_{\rm cur} = \frac{3}{2}\left(\frac{E_{\rm e}(r)}{m_{\rm e}c^2}\right)^3 \frac{c}{s}\hbar \ , \tag{6}$$

where $m_{\rm e}$ is the electron mass, c the light speed, s the radius of curvature and $\hbar$ the Planck constant. These curvature photons will be converted into secondary electron-position pairs if their energy satisfies (e.g., Ruderman & Sutherland 1975; Cheng & Zhang 1999):

$$E_{\rm cur} \geq \frac{2m_{\rm e}c^2}{15}\frac{B_{\rm q}}{B(r)} \equiv E_{\rm crit} = 3B_{12}^{-1} \ {\rm MeV} \ , \tag{7}$$

where $B_{\rm q} = 4.4 \times 10^{13}$ G is the quantum critical field, and B_{12} is the magnetic field in units of 10^{12} G. From this condition and by assuming the magnetic field near the star surface to be dipolar, we can estimate the radius $r_{\rm s}$ where the secondary $e^{\pm}$ are produced as (Zhang & Jiang 2005, 2006)

$$r_{\rm s} \simeq \left(\frac{15E_{\rm cur}}{2mc^2}\frac{B}{B_{\rm q}}\right)^{1/3} R_0 \ , \tag{8}$$

where R_0 is the neutron star radius. The secondary $e^{\pm}$ pairs will loss energy through synchrotron radiation with a characteristic energy

$$E_{\rm syn} = \frac{3}{2}\left(\frac{E_{\rm cur}}{2m_{\rm e}c^2}\right)^2 \frac{e\hbar B(r)}{m_{\rm e}c} \ . \tag{9}$$

Generally, the condition $E_{\rm syn} > E_{\rm crit}$ is satisfied, so a cascade will start and develop until this condition fails. At the end of such cascade, each incoming primary electron/positron can produce

$$N_{e^{\pm}} \simeq \frac{E_{\rm e}(r)}{E_{\rm crit}} \tag{10}$$

secondary electron-position pairs. So the total pair production rate can be estimated as

$$\dot{N}_{e^{\pm}} = f(\bar{r})\dot{N}_{\rm GJ}N_{e^{\pm}} \ , \tag{11}$$

where $\dot{N}_{\rm GJ}$ is the Goldreich-Julian current.

Not all of the cascade $e^{\pm}$ can leave the light cylinder. According to Zhang & Cheng (2001), just those in the open filed lines can escape. The number of escaped $e^{\pm}$ can be described by parameter ξ,

$$\xi \sim \frac{1}{2}\frac{r_{\rm s}}{R_{\rm L}} \ . \tag{12}$$

Therefore, the number that are just outside the light cylinder is given by

$$\dot{N}'_{e^{\pm}} = \xi\dot{N}_{e^{\pm}} = \zeta f(\bar{r})\dot{N}_{\rm GJ}N_{e^{\pm}} \ . \tag{13}$$

Outside the light cylinder, the $e^{\pm}$ move out with the pulsar wind. The plasma frequency of these $e^{\pm}$ at distance d_0 from the pulsar is $f_P = (1/2\pi)\sqrt{(4\pi n_{\pm}e^2/m_{\rm e})}$, where $n_{\pm} = \dot{N}'_{e^{\pm}}/4\pi d_0^2 c$. It can be shown that $f_P \gg P^{-1}$ at the light cylinder, so electromagnetic waves of low frequencies will push the $e^{\pm}$ plasma until $f_{\rm P} = P^{-1}$, or equipartition between the electromagnetic waves and the kinetic energy of the charged particles (Chi et al. 1996; Zhang & Cheng 2001), i.e.,

$$n_{\pm}(d_0)E_{\rm equi} = \frac{B^2(d_0)}{4\pi} \ , \tag{14}$$

where $B(d_0) = B(\frac{R_0}{R_{\rm L}})^3(\frac{R_{\rm L}}{d_0})$ is the magnetic field at distance d_0. From above equations, we can determine the equipartition energy of the accelerated particles by

$$E_{\rm equi} = 5.78 \times 10^7 B^2 P^{-4} / \dot{N}'_{e^\pm} \ {\rm eV} \ . \tag{15}$$

As described by Chi et al. (1996) and Zhang & Cheng (2001), after taking the adiabatic energy loss into account, the particle energy ejected into the interstellar medium is about one order of magnitude lower than the equipartition energy $E_{\rm equi}$, which means the ejected $e^\pm$ energy is about $E_{\rm e} = 0.1E_{\rm equi}$. So the corresponding number of $e^\pm$ per unit time and per unit energy is given by

$$Q_{e^\pm} = \frac{\dot{N}_{e^\pm}}{E_{\rm e}} \ . \tag{16}$$

3 POPULATION OF GALACTIC MATURE γ-RAY PULSARS

In the nine normal gamma ray pulsars, five of them have characteristic ages less than 10^5 yr (e.g. Thompson 2003). Gamma-ray pulsars with ages greater than 10^6 yr have not detected so far. Based on the revised outer gap model (Zhang et al. 2004), Cheng et al. (2004) have studied the properties of mature pulsars. After taking the geometry effect of inclination angle into consideration, they found there are many mature pulsars with soft gamma ray spectra. The relatively weak flux makes it difficult to detect by *EGRET*, and could be checked with a more sensitive detector like *GLAST*. Generally, the new outer gap model can predict more gamma ray pulsar with ages greater than 10^6 yr. In this section using a Monte Carlo method (e.g. Sturner & Dermer 1996; Cheng & Zhang 1998; Jiang & Zhang 2006), we check the properties of mature pulsars.

3.1 Monte Carlo Method

In our simulation, we use the following assumptions: (1) The pulsar ages are randomly selected from 10^5 to 2×10^7 yr, the birthrate is taken as $\dot{N}_{\rm NS} \sim 2$ per century, the initial period from a normal distribution with mean $\langle P_0 \rangle = 0.2$ s and standard deviation $\sigma_{\langle P_0 \rangle} = 0.15$ s. (2) The initial magnetic field distribution is assumed to be a Gaussian in $\log B$, with a mean $\log B({\rm G}) = 12.45$ and a dispersion $\sigma_{\langle \log B\,({\rm G})\rangle} = 0.35$. We ignore the field decay in our simulation. (3) The birth position for each pulsar is assumed from the distribution (Paczyński 1990) $\rho_z(z) = (1/z_{\rm exp})\exp(-|z|/z_{\rm exp})$ and $\rho_R(R) = (a_R/R^2_{\rm exp})\ R_{\rm exp}(-R/R_{\rm exp})$, where z is the distance from the Galactic plane, R the distance from the Galactic center, $z_{\rm exp} = 75$ pc, $a_R = [1 - e^{-R_{\rm max}/R_{\rm exp}}(1 + R_{\rm max}/R_{\rm exp})]^{-1}$, $R_{\rm exp} = 4.5$ kpc and $R_{\rm max} = 20$ kpc (e.g., Paczyński 1990; Sturner & Dermer 1996). (4) The inclination angle (α) of each pulsar is chosen randomly from a flat distribution (Biggs 1990), while we do not take the evolution effect into account. (5) The initial velocity of each pulsar is the vector sum of the circular velocity at the birth location and a random velocity from the supernova explosion (Paczyński 1990). The circular velocity is determined by the Galactic gravitational potential and the random velocity follows a Maxwellian distribution with a dispersion of three dimensional velocity = $\sqrt{3} \times 100\,{\rm km\,s^{-1}}$ (Lorimer et al. 1997). The period at time t is given by $P(t) = (P_0 + 1.95 \times 10^{-39} B^2 t)^{1/2}$. The pulsar position at time t is determined by following its motion in the Galactic gravitational potential. Using the equations given by Paczyński (1990) for the given initial velocity, the orbit integrations are performed using the 4th order Runge-Kutta method with variable time step on the variables R, V_R, z, V_Z and ϕ. Then the sky position and the distance of the simulated pulsar is calculated. (6) In order to compare the simulated results with the observed sample, we simulated nine surveys including Molonglo 2, Green Bank 2, Green Bank 3, Aricibo 2, Aricibo 3, Parkes 1, Parkes 2, Jodrell Bank 2 (see Gonthier et al. 2002 and references there in) and the Parks Multibeam Pulsar surveys (Manchester et al. 2001). We use the Dewey et al. (1985) formula and the surveys parameters presented by Gonthier et al. (2002) and Manchester et al. (2001) to calculate the minimum radio threshold, $S_{\rm min}$. The sky temperature is obtained using the program from ATNF and scaled to the observing frequencies using a –2.6 power law of frequency

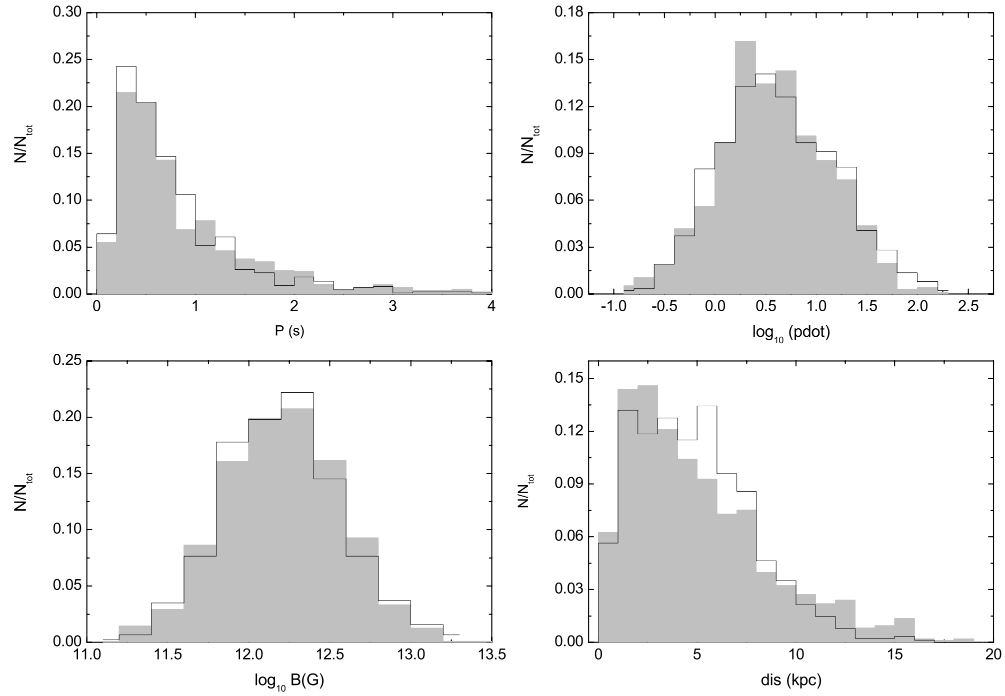

Fig. 1 Normalized number distributions $(\mathrm{N}/\mathrm{N}_{\mathrm{tot}})$ of the simulated radio pulsars and the observed pulsars. The shaded histogram shows the simulated pulsars and the solid histogram the observed pulsars.

dependence. We use the model of Cordes & Lazio (2002) to calculate the dispersion measure. Pulsar satisfying $L_{400}/d^2 \geq S_{\min}$ are considered to be radio-detectable, L_{400} being the radio luminosity at 400 MHz in units of mJy kpc^2 and d, the distance to the pulsar in units of kpc. L_{400} is estimated from the following distribution: $\rho_{L_{400}} = 0.5\lambda^2 \exp(-\lambda)$ (Narayan & Ostriker 1990), where $\lambda = 3.6[\log(L_{400}/\langle L_{400}\rangle) + 1.8]$, and $\log\langle L_{400}\rangle = (2/3)\log B_{12} + (4/3)\log P + 1.63$. We use the relation $f = 0.09[\log(P) - 1]^2 + 0.03$ found by Tauris & Manchester (1998) to determine the beam direction in our simulation. Then, a sample pulsar with a given period P is chosen in one out of $f_r(P)^{-1}$ cases using the Monte Carlo method. Using the above assumptions, we obtain a sample of pulsars that contains radio loud and radio quiet pulsars. In our simulation, by assuming a pulsar birthrate of $\dot{N}_{\mathrm{NS}} = 1.5$ per century, we obtain about 1056 radio loud mature pulsars, in fair agreement with the observed number of 888. In Figure 1, we give a comparison between the observed radio pulsars and the simulated radio pulsars. The shaded histogram corresponds to the simulated pulsars and the solid histogram to the observed. We can see that the simulated results are consistent with the observations.

3.2 Spatial Distribution of Simulated Gamma-ray Pulsars

For each pulsar, if the fractional size at the inner boundary $f(r_{\mathrm{in}}) < 1$, then it is a gamma ray pulsar. The population of simulated gamma-ray pulsars consists of radio loud and radio quiet pulsars. The former is those pulsars which can be detected by radio detectors, and the latter is those with radio flux less than the threshold of detectors or whose radio emission toward us is not detected. In the outer gap model, the gamma-ray pulsars will contribute to the diffuse Galactic positrons, so it is useful to investigate the spatial distribution of these pulsars.

In Figure 2, we display the radial and height distributions of the gamma ray pulsars. We use a gamma function to fit to model the distribution of R (the best-fit parameters are $A = 0.036$, $B = 1.29$, $C = 2.34$),

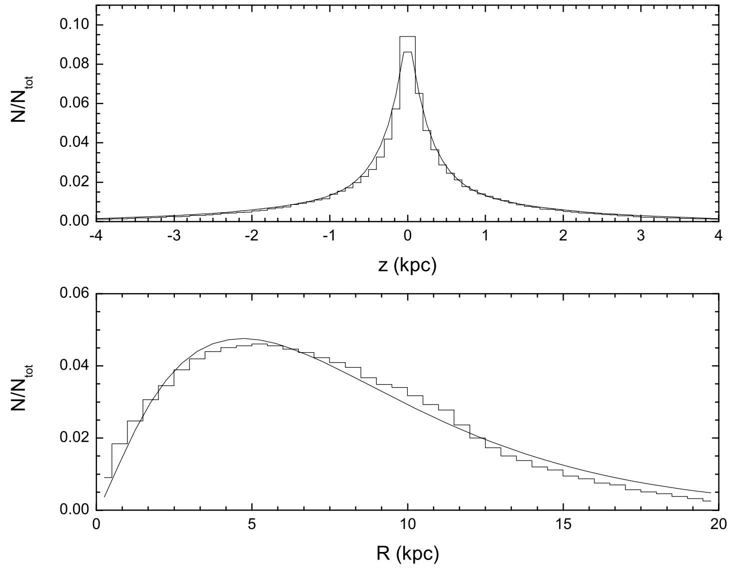

Fig. 2 Normalized distributions of z and R of the simulated gamma-ray pulsars. The solid lines show the best fits.

$$\rho(R) = A\left(\frac{R}{8.5}\right)^B \exp\left(-C\left[\frac{R-8.5}{8.5}\right]\right), \tag{17}$$

and to fit the z-distribution, we use an exponential function

$$\rho(z) = D_1\text{exp}(-|z|/E_1) + D_2\text{exp}(-|z|/E_2), \tag{18}$$

with the parameters $D_1 = 0.08$, $E_1 = 0.18$, $D_2 = 0.03$ and $E_2 = 1.04$. We can see that most of the pulsars are concentrated on the disk.

4 POSITRON FRACTION FROM MATURE GAMMA-RAY PULSARS

4.1 Positron Production Rate of Galactic Mature Pulsars

In the new version of the outer gap model, the pulsar is a gamma-ray pulsar if $f(r_{\rm in}) < 1$, then it can contribute the Galactic diffuse positron population. Using the outer gap model, we first determine which pulsar is a gamma ray pulsar, then calculate the positron produced by this pulsar per unit time and per unit energy. Subsequently we obtain the positron production rate from all of the gamma-ray pulsars,

$$Q^{\rm psr}_{e\pm} = \sum_{i=1}^{N} Q^{{\rm psr},i}_{e\pm}(E_i)\ , \tag{19}$$

where $Q^{{\rm psr},i}_{e\pm}(E_i)$ is the positron production rate of the ith gamma ray pulsar with energy E_i. In Figure 3 we give the positron production rate from the Galactic mature gamma ray pulsars. The positron production rate peaks at about 1 GeV. Above the peak it decreases approximately as a power-law and has a cut-off at about 100 GeV. The positron production rate for $E \geq 2$ GeV can be well approximated as

$$q^{\rm psr}_{e\pm}(E) \approx 4.4\times10^{-5}E^{-1.54}\text{exp}(-E/80.4)\ \text{GeV}^{-1}\text{g}^{-1}\text{s}^{-1}\ . \tag{20}$$

In the above equation, the total mass of our Galaxy is $M_g \approx 10^{10}M_\odot$. It can be seen that there are no significant differences with the result given by Zhang & Cheng (2001). With a small difference being present in the low energy band, our result is a little lower for $E < 2$ GeV.

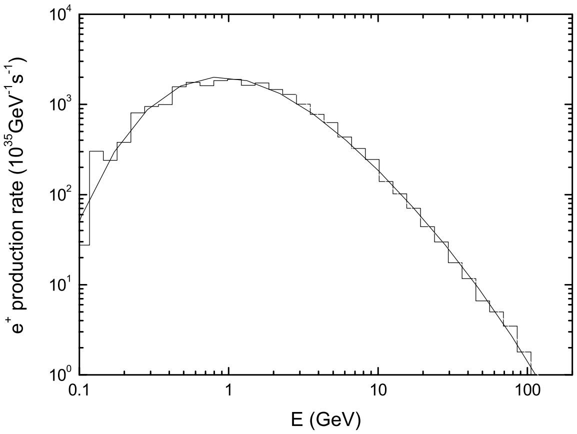

Fig. 3 Positron production rate from the simulated Galactic mature gamma ray pulsars. The solid line shows the best-fit result.

4.2 Model of Positron Propagation and the Positron Fraction

The positrons produced in the pulsar wind will propagate through the Galaxy, and be affected by the interstellar magnetic fields and energy loss via the inverse Compton and synchrotron processes. There are mainly two types of models to deal with these processes, the leaky box model and the diffuse model. The simplest model is the leaky box model, in which it is assumed that as the cosmic rays are produced and propagated homogeneously in the Galaxy, they are confined to some volume such that, when they reach the edge of the volume, they will escape with a certain probability. For simplicity, we use the leaky box model to calculate the energy spectra of positrons, in which the spectrum of electrons/positrons is given by

$$J^{(\rm psr)}_{e^\pm}(E) = \frac{1}{4\pi}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1}\int_E^\infty \mathrm{d}E' q^{\rm psr}_{e^\pm}(E') \times \exp\left[-\int_E^{E'} \frac{\mathrm{d}E''}{\lambda_e(E'')(\mathrm{d}E/\mathrm{d}x)}\right] , \tag{21}$$

where $\mathrm{d}E/\mathrm{d}x \approx 5\times 10^{-3}E^2$ is the electron (or positron) energy loss in units of GeV $\mathrm{cm}^2\ \mathrm{g}^{-1}$, including synchrotron radiation and inverse Compton scattering, $\lambda_e(E)$ is the energy dependent escape length in units of $\mathrm{g\ cm}^{-2}$, and $\lambda_e(E) = 7.0$ for $R' \le 4\,$GV and $7.0(R'/4)^{-0.4}$ for $R' > 4\,$GV, where R' being the particle rigidity.

When the positrons approach the solar system, the solar modulation can affect the positron flux. The effect is not so important when the energy of positrons is above 10 GeV. Generally, it is assumed that the solar modulation is charge sign independent, so it can minimize the system uncertainty when considering the positron fraction (the ratio of positrons to positrons plus electrons). Because we cannot distinguish the positrons from the background positrons in the measurements, we need to know the background positron flux. In the following, we use the fitting functions to describe the fluxes of the primary electrons ($J^{\rm prim}_{e^-}$), the secondary electrons ($J^{\rm sec}_{e^-}$) and positrons ($J^{\rm sec}_{e^+}$) (in units of $\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$) (Baltz & Edsjö 1999)

$$J^{\rm prim}_{e^-}(E) = \frac{0.16E^{-0.11}}{1+11E^{0.9}+3.2E^{2.15}} , \tag{22}$$

$$J^{\rm sec}_{e^-}(E) = \frac{0.7E^{0.7}}{1+470E^{1.7}+240E^{2.9}+580E^{4.2}} , \tag{23}$$

$$J^{\rm sec}_{e^+}(E) = \frac{4.5E^{0.7}}{1+650E^{2.3}+1500E^{4.2}} , \tag{24}$$

where E is in units of GeV. Then the positron fraction which includes the contribution from the Galactic mature gamma-ray pulsars is calculated as

$$R_{e^+/e^\pm} = \frac{J^{\rm sec}_{e^+}+J^{\rm psr}_{e^+}}{J^{\rm sec}_{e^+}+J^{\rm psr}_{e^+}+J^{\rm sec}_{e^-}+J^{\rm prim}_{e^-}+J^{\rm psr}_{e^-}} . \tag{25}$$

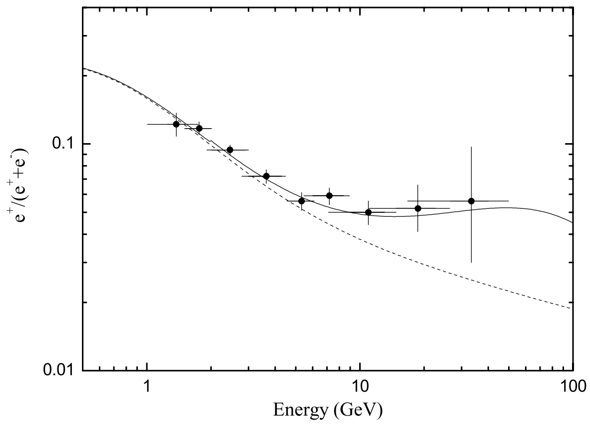

Fig. 4 Comparison of observed $e^+/(e^- + e^+)$ ratio with the predicted ones. The solid circles show the observed data by HEAT. The dash line shows the ratio of positron background and total electron background. The solid line shows the ratio including the contribution from mature gamma-ray pulsars.

In Figure 4 we show the positron fraction as a function of the positron energy. The solid circles are the observed data given by HEAT-$e^\pm$ and HEAT-pbar (Beatty et al. 2004). The dash line shows the positron fraction when the positrons are assumed to be of purely secondary origin and produced by the interaction of cosmic-ray nuclei with interstellar matter (Moskalenko & Strong 1999), the solid line shows the ratio which includes the contribution from mature gamma-ray pulsars. The contribution from mature gamma-ray pulsars becomes important above ~ 5 GeV, and the ratio peaks at about 60 GeV in the high energy range. It can be seen that the mature gamma-ray pulsars take an important role in the cosmic-ray positron fraction at the high energy range. From Figure 4, we can see that the positrons from the mature gamma-ray pulsar can explain the excess.

5 DISCUSSION AND CONCLUSIONS

We restudy the positron production from mature gamma-ray pulsars based on the revised outer gap model, which can predict more mature gamma-ray pulsars. We obtain a Monte Carlo simulation of the population of mature pulsars, which reproduces the observed radio sample. We calculate the positron fraction from all of the mature gamma-ray pulsars. The observed excess of high energy positrons above 10 GeV in our Galaxy can be explained by the contribution from mature gamma-ray pulsars with outer gaps.

The pulsar birthrate is a key parameter to constrain the possible positron contribution from mature gamma-ray pulsars, that is still not well determined to date, but is most likely to be between 1 to 2 per century, the recent study of Faucher-Giguère & Kaspi (2006) gives a birthrate of 2.8 per century, here we take a birthrate of 1.5 per century, a larger birthrate would increase the predicted positron fraction.

In the polar cap model, the positron fraction can be explained by the positron production from young gamma-ray pulsars (Harding & Ramaty 1987; Grimani 2004). To distinguish between these two types of models, more precise pulsed gamma-ray observation and positron fraction measurements are needed. The positron excess can also be explained by dark matter annihilation. New high-sensitivity experiments at above 100 GeV are needed, in order to discriminate the positron origin. PAMELA and AMS-02 may provide the hoped-for results.

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